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# MET 314 Torque Measurement

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# MET 314 Torque Measurement Lab

By

Jose Bejar

## Table of Contents

<b>INTRODUCTION .....</b>	<b>4</b>
Motivation:.....	4
Function Statement: .....	4
Requirements: .....	4
Engineering Merit: .....	4
Scope of Effort: .....	5
Success Criteria: .....	5
Success of the Project: .....	5
<b>DESIGN &amp; ANALYSIS .....</b>	<b>6</b>
Proposed Solution: .....	6
Description: .....	6
Benchmark: .....	6
Performance Predictions:.....	7
Description of Analyses:.....	7
Scope of Testing and Evaluation:.....	8
Analyses: .....	8
Device: Parts, Shapes, and Conformation:.....	8
Device Assembly and Attachments: .....	8
Tolerances, Kinematics, Ergonomics:.....	8
Technical Risk Analysis, Failure Mode Analysis, Safety Factors, Operation Limits: .....	9
<b>Methods and Construction: .....</b>	<b>10</b>
Description: .....	10
Drawing Tree: .....	11
Parts List and Labels:.....	11
Manufacturing Issues:.....	11
Assembly, Sub-assembly, Parts, Drawings:.....	12
<b>Testing Method .....</b>	<b>14</b>
Introduction:.....	14
Method:.....	14
Procedure: .....	15
Deliverables:.....	16
<b>Budget/Schedule/Project Management.....</b>	<b>17</b>
Proposed Budget: .....	17
Proposed Schedule: .....	17
Project Management .....	17
<b>Conclusion.....</b>	<b>18</b>
<b>Acknowledgements .....</b>	<b>18</b>
<b>Appendix A: Analyses .....</b>	<b>19</b>
<b>Appendix B: Drawings .....</b>	<b>33</b>
Figure 1: Bearing Housing. ....	33
Figure 3: Front Motor Plate. ....	35

Figure 4: Rear Motor Plate. ....	36
Figure 5: Motor Platform. ....	37
Figure 6: Platform Lever. ....	38
Figure 7: Shaft. ....	39
Figure 8: Shaft Housing. ....	40
Figure 9: Load Cell Base. ....	41
Figure 10: Motor Platform Assembly. ....	42
APPENDIX C – Parts List .....	43
APPENDIX D – Budget .....	44
APPENDIX E – Schedule .....	45
APPENDIX H – Testing Report .....	46
Introduction:.....	46
Method:.....	46
Procedure: .....	47
Deliverables:.....	48
APPENDIX I – Testing Data .....	50
APPENDIX J – Resume.....	54



# INTRODUCTION

## Motivation:

This project was motivated by the need of a device that would measure the torque on a motor from a thermodynamics lab setup in Hogue Hall. There are devices out there to measure the torque produced by motors, but they are too expensive. There are dynamometers for small engines such as the one used in the Power Tech Lab, but they are not small enough to be used on the air motor for the thermodynamics lab and even if they were they would be very expensive. This new measurement will allow the thermodynamics students to use the obtained torque value to take the calculations involved in the lab to another level.

## Function Statement:

A device is needed that will suspend an air motor on bearings and allow it to swing from side to side while a lever attached to the motor or base where the motor sits which will press down on a load cell that will be wired to a load cell indicator sensor meter that will display the value of the force from the motor on the cell.

## Requirements:

This device must meet the following requirements:

- The device must fit within the existing lab setup.
- It must take up no more than 2ft<sup>2</sup>
- Total weight must be under 5lb in order to keep the lab setup lightweight in case it needs to be moved.
- Any part of the device must not rust.
- Must not affect the workability of the lab setup.

## Engineering Merit:

In order to keep this device as lightweight and compact as possible while taking into consideration that the device must not rust overtime and maintain a nice clean finish there will be several calculations. The dimension of the torque arm will need to be calculated by first taking into account the maximum possible load that the motor will exert. The torque arm also has to be designed so that it deflects the least possible without increasing its dimensions too much. In order to keep the torque arm in a fixed position there will be bolts used and their diameter has to be calculated:

$$F = T / (D_{\text{bolts}} / 2),$$

Shear stress in each bolt. N = number of bolts

$$\tau = F / A_s = F / (N(\pi d^2 / 4)) = 2T / (D_{\text{bc}} N \pi d^2 / 4)$$

Required bolt diameter

$$d = [(8T) / (D_{\text{bc}} N \pi \tau)]^{1/2}$$

The diameter of the shafts also has to be calculated. Speeds and feeds have to be calculated for all the machining operations.

## Scope of Effort:

For this project the only things that will be made are the torque arm, and the base for the air motor. The load cell, digital display, and bearings will be purchased; the bolts will be obtained from the shop.

## Success Criteria:

In order for this device to be considered successful it must meet the following criteria:

- The torque arm will not break when measuring the force on the load cell.
- The torque calculated will be within a reasonable range; if it comes out to 1000lb/in something obviously went wrong.
- The torque calculated will be within 10% of the manufacturer's specs.
- Simple to manufacture.
- Long design life.

## Success of the Project:

The success of this project depends on whether or not the force read by the load cell display leads students to calculate a torque within 10% of the manufacturer's specifications. It will also be considered a successful project if on top of being within a reasonable range of torque values the device will continue to display those values for years without maintenance. Mainly, in order for this project to be considered successful will depend on if students are able to use the device after a simple explanation by the professor running the lab.

# DESIGN & ANALYSIS

## Proposed Solution:

Professor Beardsley provided insightful information to solve this problem. He mentioned that the motor could be placed on bearings and have some sort of lever on the shaft with a strain gauge. The solutions chosen for this problem includes some of those ideas. The air motor will be fixed to a platform that will have a shaft at one end that will sit on bearings so that the platform can rotate. There will be a torque arm attached to the platform where the motor will sit. This design will allow the outer casing of the motor to be free allowing the lever to push down on a load cell.

## Description:

The design for this lab must ensure that it will not rust over time, it will have a nice clean finish, and it will also not add too much weight or take up too much space. Because of this requirements the best material to fit the device is an aluminum alloy since it is light weight, it has high tensile, compression, and shear properties along with the fact that it will not rust.

There are two main functions this device will perform. The first function consists of the motor rotating about an axis concentric to the axis of the shaft. This will be achieved by placing the motor on a platform that sits on bearings at one end, refer to Figure 7 in Appendix B. This platform will have a plate perpendicular to it with a shaft pressed fitted. The shaft will slide into the bearings that are pressed in the bearing housings (Appendix B figure 1 & 2). The shafts will be machined with a 0.005" tolerance so that they have a tight fit in the platform side plates. The holes on the side plates will also be machined with a 0.005" tolerance.

The second main function consists of a torque arm (Platform lever Figure 8 Appendix B). This lever will be fixed to the motor platform and will remain horizontal while pressing down on a load cell. The load cell will be wired to a digital display that will display the load in  $\text{lb}_f$ . This load cell will sit on a jig so that its top surface is parallel with the bottom surface of the torque lever. The wires on the strain gauge of the load cell will be soldered to the digital display to prevent any loose wiring interruptions. The students now just need to multiply the load on the display by the length of the lever to obtain the torque.

## Benchmark:

In the Power Tech room there are two engines with similar torque measuring devices. They consist of a metal alloy arm attached to the engine's output shaft with a strain gauge; this arm rests on a bar that is attached to the stand where the motor sits. The project for the thermodynamics lab torque measurement is a similar design only made to a smaller scale. The arm for this project will not be slotted as the one in the Power Tech room; instead it will be a solid rectangular bar that will rest horizontally on a load cell. Instead of the water clutch system the dynamometer in Power Tech uses, the thermodynamics lab air motor will rest on a platform that sits on two bearings.

## Performance Predictions:

All components are predicted to fit well within the existing lab setup and without adding too much extra weight. Also, because all parts of this device except the bolts and bearings are made of an aluminum alloy, it is predicted that this device will not rust and it will maintain a clean surface finish.

Once this device is fully built and functional, it is predicted that the motor will apply a force of around 6 lb<sub>f</sub> on the load cell. This will lead to a torque calculation of 36 in-lb on the top end. It is also predicted that the torque lever will stay within its elastic modulus throughout the testing process, which will prolong its lifetime.

This lab will always be housed indoors and therefore temperature changes do not have to be taken into account when designing it. This means the components will not be exposed to extreme temperatures that could affect their performance.

## Description of Analyses:

### Platform Lever:

In order to design the lever that will transfer the torque from the motor and place a force on the load cell, the predicted load on the cell has to be calculated ( $T=FD$ ). Then pick the length and height of the lever and calculate the width using  $\text{stress} = M/S$  where  $S = WH^2/6$  and  $M$  is the maximum moment on the lever. The max deflection at the non-fixed end will be calculated in order to decide if the calculated dimensions are enough for a small deflection.

### Bolts:

The bolts will not be machined, but the right diameter still has to be chosen to prevent failure. The bearing housing plate has to be bolted to the lab set up platform; the motor platform has to be bolted to the side plates that will hold the shaft that sits on the bearings. Use the equations  $F = 2T/D$ ,  $\text{shear} = 2T/DN$ , and  $\text{diameter of bolt} = (8T/DN \cdot \pi \cdot \text{shear})^{1/2}$ .

### Shaft:

The shaft on which the motor platform sits is subjected to a shear force. In order to prevent failure the diameter has to be calculated using  $\text{shear} = F/\text{surface area}$ . The force depends on the weight of the motor and its components plus the reaction force from the torque arm.

### Bearing Housing:

The bearing housing is subjected to the compressive load of the motor and other components. It is a 1.5" plate and with components lighter than 20lbs there is no need to worry about these plates failing.

## Scope of Testing and Evaluation:

The impact tester can be used to test the key manufactured for the coupler. This can ensure that the key will not fail while students are working on the lab. The same test can be done to the torque arm.

## Analyses:

Solve for the diameter of the bolts that will be used to attach the torque arm to the shaft and also solve for the geometry of the torque arm. The diameter for the bolts that hold the motor to the platform that swivels on bearings also have to be calculated. The diameter of the shaft that sits on the bearings has to be solved for. Take into account that these calculations have to use a safety factor of 1.5 and that the material used is Aluminum 6061. In order not to add too much weight the total weight of the device can be calculated in solid works along with the surface area to see how much space it will take up.

## Device: Parts, Shapes, and Conformation:

The professor who offered this project wants the final device to withstand rust and have a fine clean finish. Because of this then the chosen material is aluminum. It is easy to machine and the final surface finish is almost like it was polished and it also will not rust. In order to achieve this, when the parts are machined a high spindle speed and slow feedrate will be used.

## Device Assembly and Attachments:

This device has three main sections of parts. The load cell will be wired to the digital display, the wires will be soldered to provide a good connection. The torque arm will be machined and bolted to the bottom of the motor platform.

The platform where the motor will sit is the main focus. The endplate will have to be drilled together with the platform to ensure hole concentricity. The holes on the platform endplate and bearing housing will be drilled and reamed to provide good hole concentricity and a tighter fit for when the bearings and shafts are pressed in. The motor platform can be assembled prior to bolting the device to the lab set up platform.

## Tolerances, Kinematics, Ergonomics:

Every hole, diameter, and overall length of any part should be machined to within 0.005" in order to guarantee that the edges and corners of this device will line up. This will also ensure a proper press fit for the shaft onto the side plate of the platform and between the bearing and the bearing housing plate. If the holes are drilled to this tolerance they will not properly align and the fitment of the parts will look crooked. This will also ensure that the platform where the motor sits will be as parallel as possible to the bottom platform and provide a better power transfer and not add any unwanted stresses on the device and motor shaft.

## Technical Risk Analysis, Failure Mode Analysis, Safety Factors, Operation Limits:

In order to machine the parts for this device it has to be taken into account that the MET 355 class leaves their projects in the CNC machines throughout the quarter and there usually is not much room to load projects while they are running their class projects. It is important to keep track of how the advanced machining class is doing and when they leave the CNC machines open for others. The same has to be taken into account for the MET 255 class since most of the time they use the lathes and the manual milling machines.

Another risk is the availability of funds for the components of the project. For the most part aluminum is relatively cheap and hardware can be obtained from the CWU shop at no cost. Since this is a project that will stay at CWU to be used by students the department may donate funds or materials to complete this project.

One way this device may fail is if the motor is started prior to placing the torque lever on the load cell. If this happens then the lever will strike the load cell or the steel platform and the lever may bend or break and may also break the load cell. This is a critical load scenario where the torque arm and the load cell will experience a higher load than they were designed for. If extra weight is placed on the motor platform then the shaft that sits on the bearings may experience a higher load than it was designed for, this will create a higher shear force than it can handle and therefore it may shear. For this reason all parts must be designed with a safety factor of 1.5 at a minimum.

It is important to only use this device with the specified motor in the lab. It is not designed to withstand the torque from motors bigger than those used in the thermodynamics lab. It is also important to keep any other lab materials from hitting and damaging the load cell. This will prevent any part of the device from failing and it will extend the lifetime of the device. It is also important to keep dust and fluids from falling on the bearings since this may build up gunk or wash away the lubricant in the bearings and shorten their lifetime.

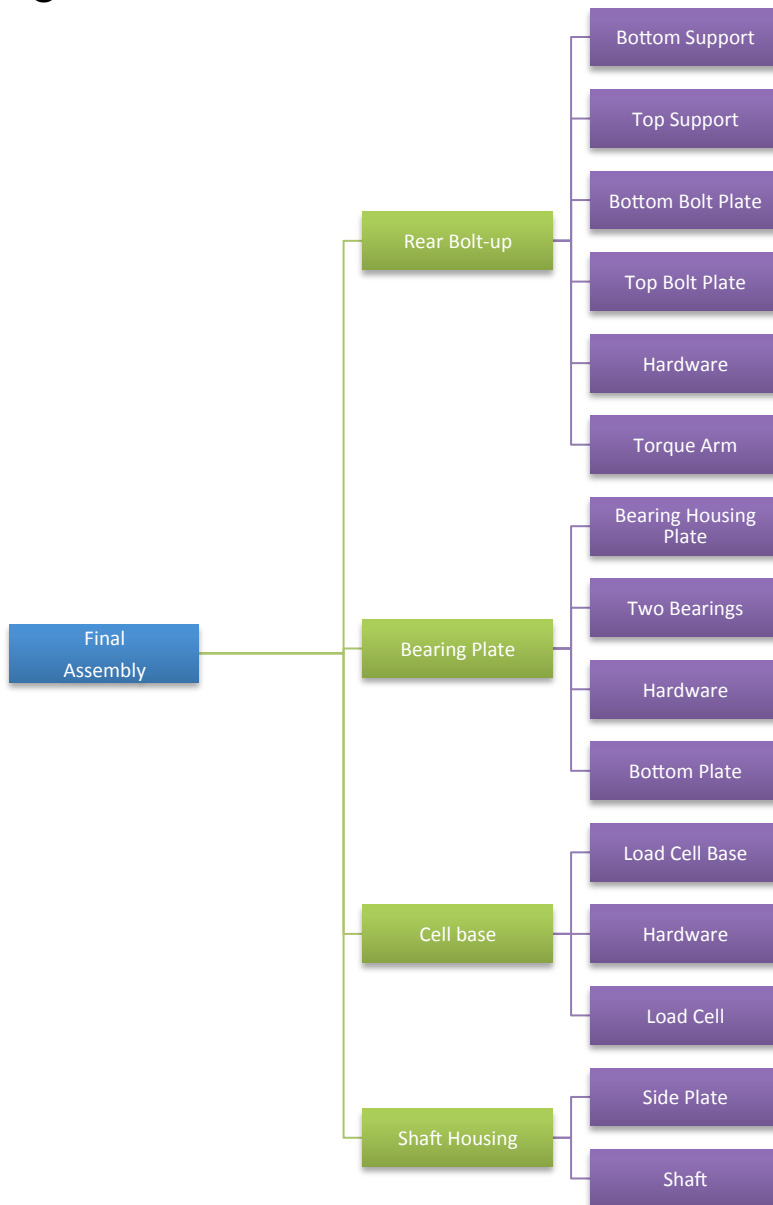
# Methods and Construction:

## Description:

Every component besides from the hardware is made out of aluminum 6061 3/8" plate or round stock. The bearing housing has bearings that slide in and will be fixed with epoxy or Loctite. The bearing housing will be welded to a platform that will bolt down to the lab setup. The motor platform has a shaft housing with the shaft pressed in and welded; this shaft slides into the bearings in the bearing housing. There are two motor bolt plates that bolt up to the top and bottom existing tapped holes on the rear of the motor. On the right end of the motor platform the torque arm is bolted using two bolts. This torque arm will press down on a load cell.

There are three main subassemblies. The first consists of the motor platform which is made up of the motor platform base with a side plate that has a shaft pressed in. There are two motor plates that hold the motor. All of these parts are bolted down with hardware that will be purchased. The second subassembly consists of the bearing housing that has bearings pressed in. The third subassembly only consists of the torque lever which will be bolted to the motor platform.

## Drawing Tree:



## Parts List and Labels:

Refer to Appendix C for a detailed parts list; it contains all the information necessary to complete the build.

## Manufacturing Issues:

Instead of using socket cap screws to assemble this device, all the parts that go together will be welded. One possible problem is welding misaligned parts, if this happens the parts will



have to be machined from scratch again. Although bolting the parts together is a safer route, this does not provide a rigid structure and is more prone to fatigue failure over time.

Another issue that can get in the way is not turning the shafts to the right diameter. If the outer diameter is too large then it will be hard to press them into the platform side plates. If the outer diameter is too small then the shafts will slide out of the platform side plate. This issue can also affect their fitment into the bearings.

If the hole for the bearings is too big then the bearings will slide out. If this happens, the bearing housing is useless and has to be machined again from the beginning. A slide fit is optimal to increase the life of the bearings, a very tight interference fit will create too many stresses in the bearing housing and the bearings themselves.

While setting up the lathe to bore the hole for the bearings a problem was encountered. The 4-jaw chucks available at the CWU shop do not provide the proper clearance in the back to bore the hole for the bearing housing. Fortunately the shop has an indexable boring head for the milling machine and that fixed a problem.

One big problem that was encountered is related to the electrical portion of this project. The load cell obtained was very cheap and therefore it is not of the best quality. This load cell does not put out the required precision for the load value. Because this motor is only rated at 36 lb-in of max running torque, a small change in the load read by the load cell can mean a large change in the torque value. Therefore a better quality load cell is required and this cost may be over the set budget.

## Assembly, Sub-assembly, Parts, Drawings:

It is important that all the machining is precise for the assembly to go smoothly. The assembly has a required sequence, which allows the components to fit correctly. The assembly goes as follows:

1. The torque arm will be machined.
  - The holes will be drilled on the milling machine for precision.
2. The platform side plate will be machined.
  - The shaft hole will be drilled and reamed.
  - The shaft will be turned to match the hole and then pressed in.
  - The holes on the top will be drilled on the mill or drill press.
3. The motor bolt plates will be machined.
  - Machined to precision on the mill.
  - The holes will be drilled on the mill or drill press.
  - The holes will be tapped by hand.
4. The motor platform will be machined and assembled.
  - The platform will be machined on the mill, the holes will be drilled to match those of the motor bolt plates.
  - The side plate will be bolted to the platform (Can weld if possible).
  - The bolt plates will be bolted to the platform.
  - The torque arm will be bolted to the platform.
5. The bearing housing plate will be machined.
  - Machined to precision on the mill.

- Holes will be drilled and tapped by hand.
  - The bearing hole will be drilled and reamed.
  - The bearings will be pressed in.
  - Bottom plate will be machined on the mill, holes will be drilled.
  - Bolt or weld bearing housing to bottom plate.
6. Bolting assembly to the main lab set up platform.
- The bearing housing bottom plate will be bolted to the main lab setup platform then the shaft from motor platform will slide into the bearings.
  - The load cell base will be machined, holes will be drilled and tapped (by hand).

# Testing Method

## Introduction:

A testing method was established in order to prove that the device built will measure the torque of the motor to within reasonable values. A parallel beam load cell is used and it seems that it may give different load values if the load is placed on different sections of the load cell. Also, the weight of the whole device including the load cell, the digital read out, and the hardware must be five pounds or less. Besides from those two requirements, the main requirement that was tested for is the torque value, which was supposed to be  $\pm 2$  lb-in of the manufacturer's specifications. When testing the load cell the values obtained will be from a static load, and the weight will be a reading from a scale. The torque values will be obtained from running the air motor hooked up to the water pump at a set inlet pressure while limiting the RPM by closing the outlet of the water pump.

## Method:

In order to run any tests several things are needed. First, the lab rig and all components must be obtained. This includes water tank, hoses, RPM meter, calibration weights, oil mister, and the lab rig with water pump fitted with inlet and outlet pipes. A source of compressed air is very important as well as a second person to help with reading and calling out values. A scale is needed to weight the device and a jig must be made to test the load cell.

The values from the torque test will be put into excel. These values include RPM, load, and length of torque arm. Using excel the torque can be calculated as well as the horsepower and both of these values can be graphed where RPM is on the X-axis and torque and horsepower are on the Y-axis.

To weigh the device it must first be removed from the rig and place everything on the scale at once including the load cell and readout. In order to test the load cell a jig that fits concentric with the holes on the cell must be machined. Finally, to test the whole device the air motor will be ran in conjunction with the water pump and a water source, which is the source that will place a load on the motor allowing it to produce torque.

Due to safety reasons there are some limitations on the operation of this device. The air motor and the water pump are quite old and therefore it may not be safe to push the motor to 3000 RPM at an inlet pressure of 100 psi. At an inlet pressure of just 60 psi the pressure at the outlet of the water pump rises to over 100 psi when the valve is closed in order to lower the RPM and obtain load cell values at lower RPM.

The precision of the torque values will be affected by the precision to which the length of the torque arm was machined; it will also be affected by the accuracy of the load cell and the precision to which the digital readout calculates the load values. The precision to which the components are machined will not affect the overall performance of the device, except for the concentricity of the bearings with the motor's shaft, but this can be easily adjusted.

The data will be presented in tables and graphs. The test for the load cell will have several load values of different sections of the load cell and they will be organized in a table. The weight of the device is not as important yet it will be placed in a table comparing the requirement and the actual value. The torque values will be calculated in a spreadsheet and presented in a table and a graph.

## Procedure:

Load Cell Calibration: The load cell used is a parallel beam load cell and therefore there is not center spot where the load should be placed. Because of this one is not sure where to place the load in order to obtain the best results. This test can be done anywhere as long as the load cell, digital readout, calibration weight (200g was used), test jig, and battery are present. This test can take up to two hours including the machining time spent making the test jig. For this test access to the machine shop is required.

Weight of Device: This is a simple test to check for a requirement. This requirement was placed in order to keep the lab rig as light as possible. Overall it will not affect the torque results. The portion that could affect the torque values is all the components that turn with the air motor, that includes both rear bolt plates, upper and lower supports, torque arm, shaft housing, shaft and nut, and all the bolts and pins. Because all these components turn with the bearings which are practically a frictionless surface it is like the motor has no extra mass to turn. This test can be done anywhere where a scale is available and it should take no more than 45 minutes including tear down and reassembly time.

Torque Measurement: For this test not every sensor on the lab rig is needed. The only components needed are the motor, water pump, some hoses, oil mister, water tank, compressed air, RPM meter, and the torque measuring device. This test can take between two to three hours depending on the knowledge of how everything is hooked up.

**See Appendix H for test results procedures and Appendix I for test results.**

## Deliverables:

The final results are mass values in pounds, load cell values in grams, and torque values in lb-in. In order for these torque values to be considered successful then they must be within 5% of the manufacturer's specifications. If the values are father off then it must be due to concentricity issues, and the electronic components being of low quality.

A parallel beam load cell seems like a new thing around this department and nobody had good input on them. Using a button load cell is simple since the load just has to be centered on it. On the parallel beam load cell there is enough surface area that the load can be moved around. What is not known is if the load reading will change if the load is placed on different spots on the load cell. Because of this a test was designed. This test would define if the load cell would have to be fixed in place or allowed to move freely while running the lab. In the end it was discovered that no matter where the load was placed the load reading did not change, but only by a few grams. This change in the load reading will not make a big impact on the overall torque calculations since those loads are expected to be a couple thousand grams.

The lab rig itself is quite a heavy object and therefore it was set forth that the torque measuring device must not weigh over five pounds. There was no clear prediction of how much the whole device would weigh since in the end it would not affect the workability of the device. It was more of a requirement to keep in mind and not something to really try to achieve. In the end the device ended up being around 4.80 lb.

For the torque calculations a test was devised in order to try and match the manufacturer's torque specs. The manufacturer provided a graph of the torque at different inlet pressures and through the maximum limit of RPM. The graphs in Appendix I show the results. These results are not close at all to what the manufacturer specified. This is due to the motor and water pump being a little old, but mostly because the electronic components, that is the load cell and digital readout are not of the highest quality and therefore do not produce accurate results with good repeatability. These two items are far more accurate with a static load, but when vibrations are added the digital readout cannot keep up with the changes in load on the load cell. The best way to fix this problem is to somehow connect the load cell to a data logger program such as LabVIEW and take a moving average to get rid of all the noise.

# Budget/Schedule/Project Management

## Proposed Budget:

This is a small project that requires a small amount of materials and therefore the budget is calculated to be \$65.21. The funding for this project will come out of the student's pocket and perhaps some materials may be obtained from the department since this project will stay here at CWU. Most of the materials including aluminum plates, bearings, load cell, and digital display will be bought off of ebay. An itemized list including material, quantity, and cost can be found in Appendix C.

All the machining and assembly labor will be done at the CWU machine shop, which provides the necessary tooling and environment to complete these processes. No labor for this project will be outsourced, this allows for a smaller budget.

## Proposed Schedule:

A tentative schedule that is subject to change was created to help organize this project and ensure that it will be completed on time. This schedule is located in Appendix D. The schedule outlines the steps and time it took to write up the proposal. It points out the main tasks and in some cases subtasks. It is broken up into three sections, one for each quarter. The quarter in which the project is built is organized in a way so that the project is finished by the end of the quarter if the outlined schedule is followed. The schedule also points out milestones, in order to stay on track those milestones need to be reached by the deadline. The estimated time to complete the manufacturing portion of this project is 101 hours.

## Project Management

### Human Resources:

There is one other student working on this same project each on their own. There will be two projects all with the same purpose. Talking to each other helps bounce off ideas and make sure that the project will have a good outcome.

### Physical Resources:

The CWU machine shop and machining instructors will be influential when it comes to machining anything in the most efficient way.

### Soft Resources:

SolidWorks is an incredible tool to help design this project. It allows for quick editing of current designs or for a complete new design to be brought to life.

# Conclusion

This device is designed to measure the torque output of the air motor for the thermodynamics class laboratory. The design is appropriate because it is made of a material that will not rust, the device does not interfere with any other part of the lab setup, and the output reading has a resolution appropriate for the data calculations involved with the lab.

The Mechanical Engineering department here at CWU offers classes such as machining, welding, mechanical design, and strength of materials. These classes teach the necessary skills required to design and build this project. The mechanical engineering department also offers enough resources such as the machine shop, which contains enough tools and materials to machine the parts for the torque measuring device.

# Acknowledgements

Acknowledgements of gratitude go out to the following people who have helped at different stages of this project.

- Professor Beardsley for providing this project.
- Classmates Sergio Flores, David Sedano, and Jose Garcia for their help with SolidWorks.
- Classmate Logan for his continuous updates on the requirements of the project.
- Professor Johnson and Pringle for their input on the proposal.
- Matt Burvee and Ted Bramble for their input on machining the project.

# Appendix A: Analyses

Image 1: Torque Lever Dimensions.

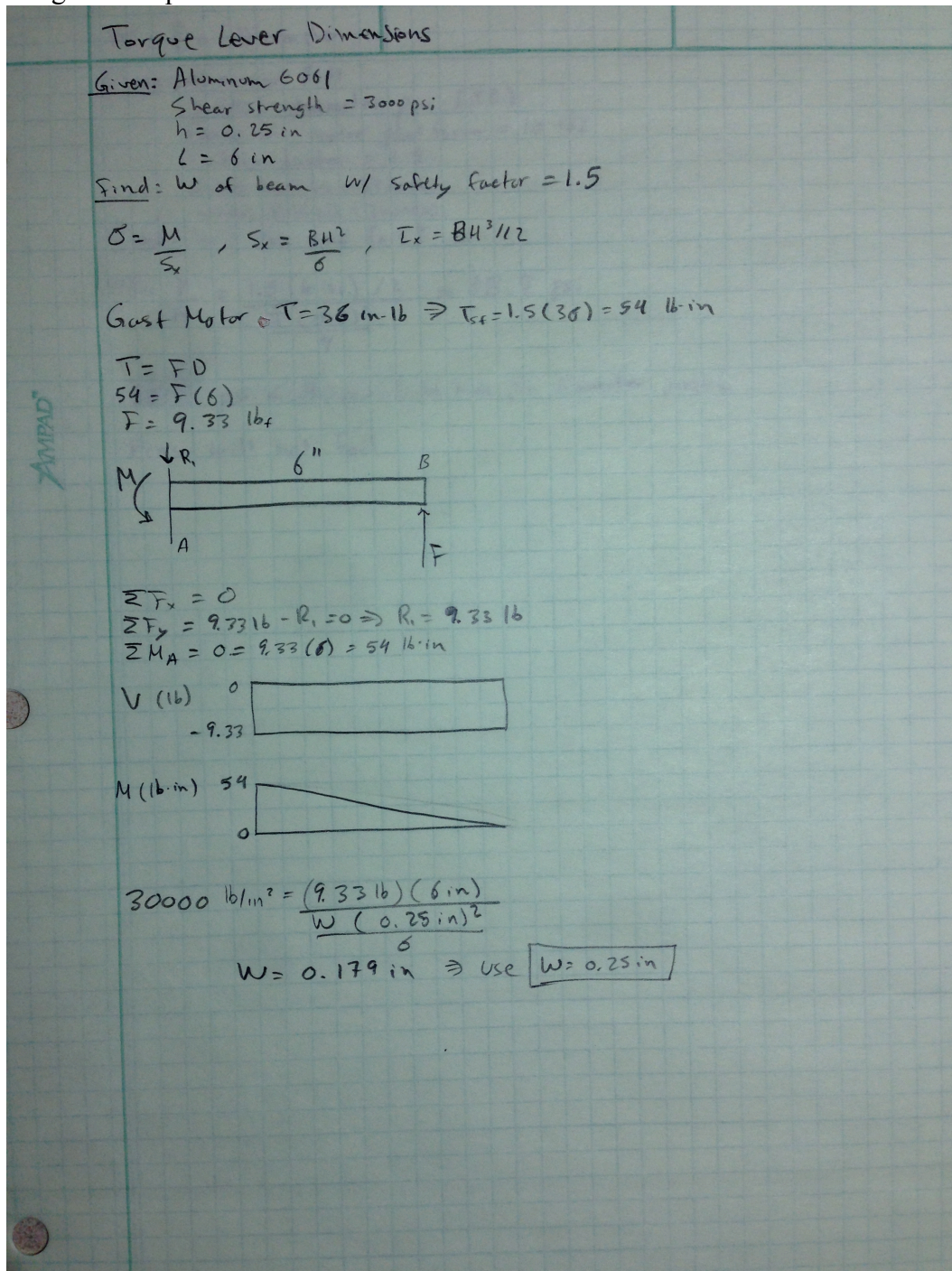




Image 2: Failure of 1/2" pin.

1/2" Pin Diameter

Given: Aluminum 6061  
0.500" diameter pin (x2)  
Force on motor platform = 10 lbf  
Safety factor = 1.5  
Shear modulus = 3770 ksi  
Shear strength = 30000 psi

Find: Will the pins fail?

$$\tau = \frac{P}{A} = \frac{1.5 (10 \text{ lbf}) / 2}{\frac{\pi (0.5)^2}{4}} = 38.2 \text{ psi}$$

38.2 psi < 40 psi From min pin diameter problem

Pins will not fail

Image 3: Minimum pin diameter.

Minimum Pin Diameter

Given: Al 6061 pin (x2)  
Force on motor platform:  $F_{\max} = 15 \text{ lbf}$   
Safety factor = 1.5

Find: Min diameter of pin if it is to fail at  $\tau_{\text{fail}} = 40 \text{ psi}$

$$\frac{15 \text{ lbf}}{2} = \frac{7.5 \text{ lbf}}{1.5} = 5 \text{ lbf}$$
$$40 \frac{\text{lb}}{\text{in}^2} = \frac{5 \text{ lbf}}{\frac{\pi d^2}{4}}$$
$$\Rightarrow d = 0.40 \text{ in}$$



Image 4: Tensile force on lever bolts.

### Tensile force on lever bolts

Given: 9.33 lbf on torque lever

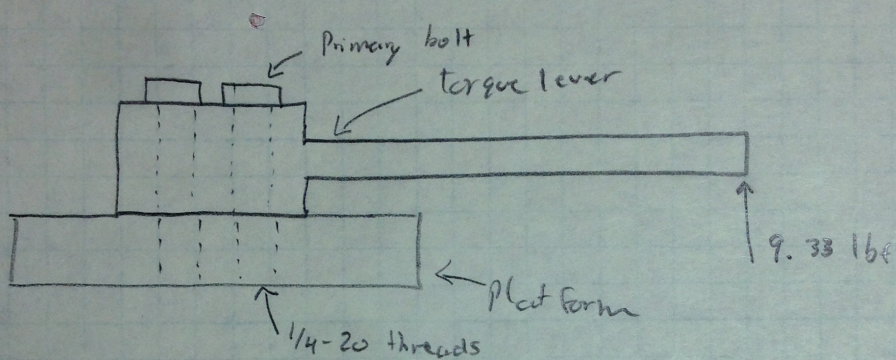
2 steel bolts hold it down

$\frac{1}{4}$ -20 bolts

Tensile stress area =  $0.0318 \text{ in}^2$

Basic major diameter =  $0.2500 \text{ in}$

Find: Tensile stress on primary bolt.



$$\sigma = \frac{F}{A} = \frac{9.33 \text{ lbf}}{0.0318 \text{ in}^2} = \boxed{293 \text{ psi}}$$

Image 5: Coupling bolts diameter



Ribbed rigid coupling bolts

Given:  $T = 56 \text{ lb}\cdot\text{in}$   
Bolts x 4  
1/4" diameter

Find: Required bolt diameter

$$F = \frac{T}{D_{bc}/2} = \frac{2T}{D_{bc}} = \frac{2(56)}{0.25} = 448 \text{ lbf}$$

$$\tau = \frac{F}{A_s} = \frac{F}{N(\pi d^2/4)} = \frac{2T}{D_{bc} N (\pi d^2/4)}$$

$$\tau = \frac{2(56)}{(0.25)(4)(\pi)(.25^2/4)} = 2282 \frac{\text{lbf}}{\text{in}^2}$$

Required bolt diameter

$$\begin{aligned} d &= \sqrt{\frac{8T}{D_{bc} N \pi \tau_d}} \\ &= \sqrt{\frac{8(56)}{(0.25)(4)(\pi)(2282 \text{ lbf/in}^2)}} \\ &= \sqrt{0.06249 \text{ in}^2} \\ &= 0.2499 \end{aligned}$$

$$d = 0.250 \text{ in} \leftarrow$$



Image 6: Key geometry

## Key Geometry

Given:  $5/8$ " shaft diameter, Hub length  $1/2$ "  
 $3/16$ " keyway width  
 $T = 56$  lb·in

Find: Key geometry

Table 11-1 Machine Elements in Mechanical Design  
 $\Rightarrow$  Use a  $\frac{3}{16}$  in square key

SAE 1018  $S_y = 54000$  psi (Table 11-4 MET 418 book)

$$\tau_d = \frac{0.5S_y}{N} = \frac{(0.5)(54000 \text{ psi})}{3} = 9000 \text{ psi}$$

$$\sigma_d = \frac{S_y}{N} = \frac{54000}{3} = 18000 \text{ psi}$$

$$L_{\min} = \frac{2T}{\tau_d DW} = \frac{2(56 \text{ lb·in})}{(9000 \text{ lb/in}^2)(5/8 \text{ in})(3/16 \text{ in})} = 0.106 \text{ inches} < \text{Hub length}$$

Appendix A2-1  $\Rightarrow L = 0.125$  in preferred  $\Rightarrow L = \frac{3}{8}$  in closer to hub length

### Key Geometry

Square key  $\frac{3}{16}$  in  $\times$   $\frac{3}{16}$  in  $\times$   $\frac{3}{8}$  in



Image 7: Lever deflection 1/4" cross section

### Deflection of torque lever

Given: Cantilever beam

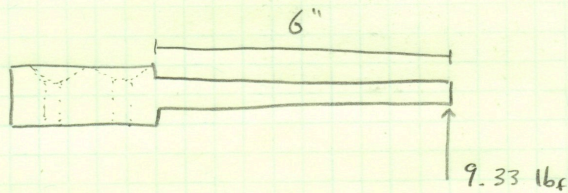
Length = 6 in

Width = 0.25 in

Height = 0.25 in

Material: Al 6061  $E = 10,000 \text{ ksi}$

Find: Deflection at non-fixed end



$$y_{\max} = \frac{PL^3}{3EI}$$

$$I = \frac{H^4}{12} = \frac{(0.25 \text{ in})^4}{12} = 0.000326 \text{ in}^4$$

$$y_{\max} = \frac{(9.33 \text{ lbf})(6 \text{ in})^3}{3(10000 \text{ ksi} \frac{\text{lbf}}{\text{in}^2})(0.000326 \text{ in}^4)}$$

$$= 0.206 \text{ in} \leftarrow \text{Deflection}$$

Too much. Redesign

Image 8: lever deflection  $\frac{1}{2}$ " cross section



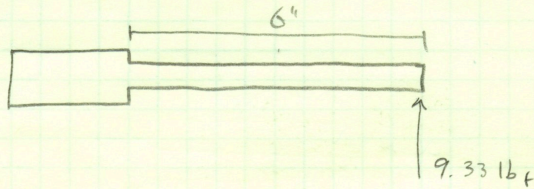
### Deflection of torque lever

Given: Cantilever beam

$$L = 6 \text{ in}, W = 0.5 \text{ in}, H = 0.5 \text{ in}$$

$$\text{Al 6061: } E = 10,000 \text{ ksi}$$

Find: Deflection at non-fixed end



$$y_{\max} = \frac{PL^3}{3EI}$$

$$I = \frac{H^4}{12} = \frac{(0.5 \text{ in})^4}{12} = 0.005208 \text{ in}^4$$

$$y_{\max} = \frac{(9.33 \text{ lbf})(6 \text{ in})^3}{3(10,000 \frac{\text{lbf}}{\text{in}^2})(0.005208 \text{ in}^4)}$$

$$= 0.012898 \text{ in}$$

$$y_{\max} = 0.013 \text{ in}$$

Max  
Deflection

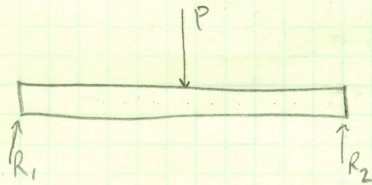


Image 9: Platform deflection

# Deflection of motor platform

Given:  $L = 5 \text{ in}$   
 $H = 0.375 \text{ in}$   
 $W = 3 \text{ in}$   
 $A16061 \ E = 10 \times 10^6 \text{ psi}$   
 $P = 10 \text{ lbf}$   
 Safety factor = 1.5

Find: Deflection in the middle



$$P_{sf} = 1.5(10) = 15 \text{ lbf}$$

$$\sum F_x = -15 \text{ lbf} + 2R = 0 \Rightarrow R_1 = R_2 = 7.5 \text{ lbf}$$

$$y_{max} = -\frac{PL^3}{48EI}$$

$$I_x = \frac{HB^3}{12} = \frac{(0.375)(3)^3}{12} = 0.84375 \text{ in}^4$$

$$y_{max} = -\frac{(15 \text{ lbf})(5 \text{ in})^3}{48(10 \times 10^6 \frac{\text{lbf}}{\text{in}^2})(0.84375 \text{ in}^4)}$$

$$y_{max} = -4.63 \times 10^{-6} \text{ in}$$

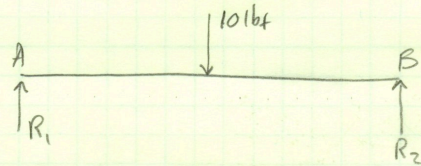
Max  
Deflection



Image 10: Platform shear moment diagrams

Given: Platform Dimensions  $\{L = 5 \text{ in}, H = 0.375 \text{ in}, W = 3 \text{ in}\}$   
 10 lb load in the middle  
 Fixed at both ends

Find: Shear & Moment diagrams, max moment & max shear -



$$\sum F_x = R_1 + R_2 - 10 \text{ lbf}$$

$$\sum M_A = 10(2.5 \text{ in}) - R_2(5) = 0 \Rightarrow R_2 = 5 \text{ lbf}$$

$$R_1 + 5 - 10 \text{ lbf} = 0 \Rightarrow R_1 = 5 \text{ lbf}$$

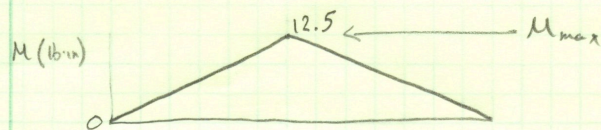
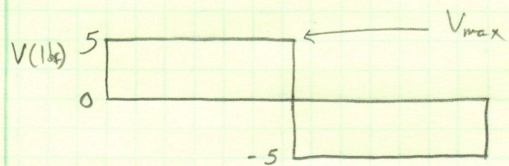


Image 11: Weight of device



### Calculating weight of device

Given: Dimensions

$$6.75 \times 0.375 \times 2.00 \text{ in}$$

$$5.75 \times 0.375 \times 2.00 \text{ in}$$

$$2(3.00 \times 0.375 \times 1.00) \text{ in}$$

$$2(3.00 \times 0.375 \times 0.750) \text{ in}$$

$$5.00 \times 0.375 \times 3.00 \text{ in}$$

$$8.00 \times 0.5 \times 0.5 \text{ in}$$

$$\text{Shaft } D = 0.5' \text{ } L = 1' \times 2$$

$$\text{Al 6061 Density} = 0.095 \text{ lbm/in}^3$$

Find: Mass of device in lbm

$$\begin{aligned} \text{Volume}_{\text{total}} &= (6.75 \times 0.375 \times 2) + (5.75 \times 0.375 \times 2) + 2(3 \times 0.375 \times 1) \\ &\quad + 2(3 \times 0.375 \times 0.750) + (5 \times 0.375 \times 3) + (8 \times 0.5 \times 0.5) \\ &\quad + \frac{\pi (0.5)^2 (1)}{4} \times 2 \\ &= 21.021 \text{ in}^3 \end{aligned}$$

$$\text{Mass} = \text{Volume} \times \text{Density}$$

$$= 21.021 \text{ in}^3 (0.095 \text{ lbm/in}^3)$$

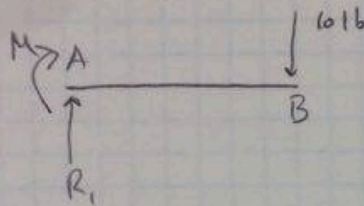
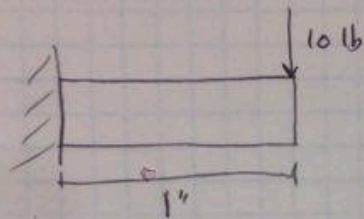
$$= 1.997 \text{ lbm}$$

$$\text{Mass} = 2.0 \text{ lbm}$$

Meets requirement

Image 12: Shaft shear moment diagrams

Given: 1" long shaft  
Fixed at one end  
10 lb load on free end  
Find: Shear & moment diagrams



$$\sum F_x = R_1 - 10 \text{ lb} = 0$$

$$R_1 = 10 \text{ lb}$$

$$\sum M_A = 0 = 10(1) = 10 \text{ lb}\cdot\text{in}$$

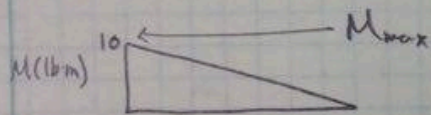
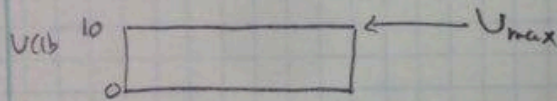




Figure 2: Bearing Housing Platform.

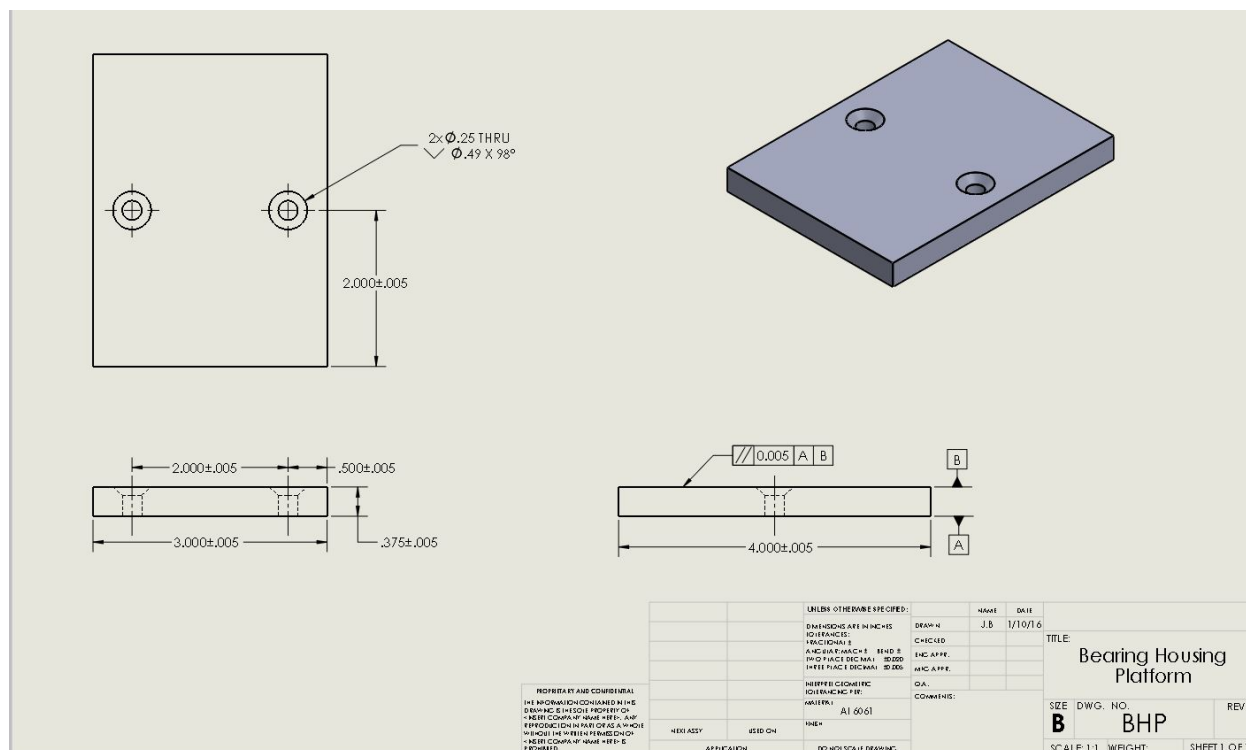




Figure 3: Front Motor Plate.

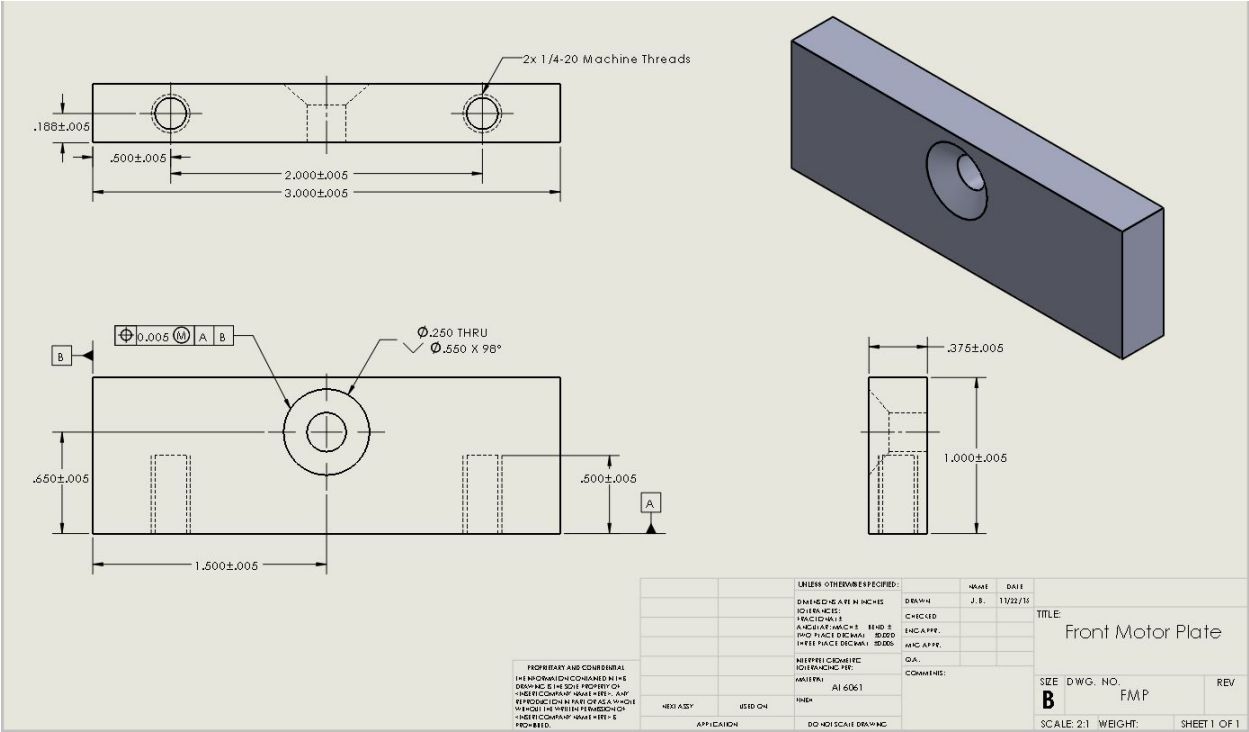




Figure 4: Rear Motor Plate.

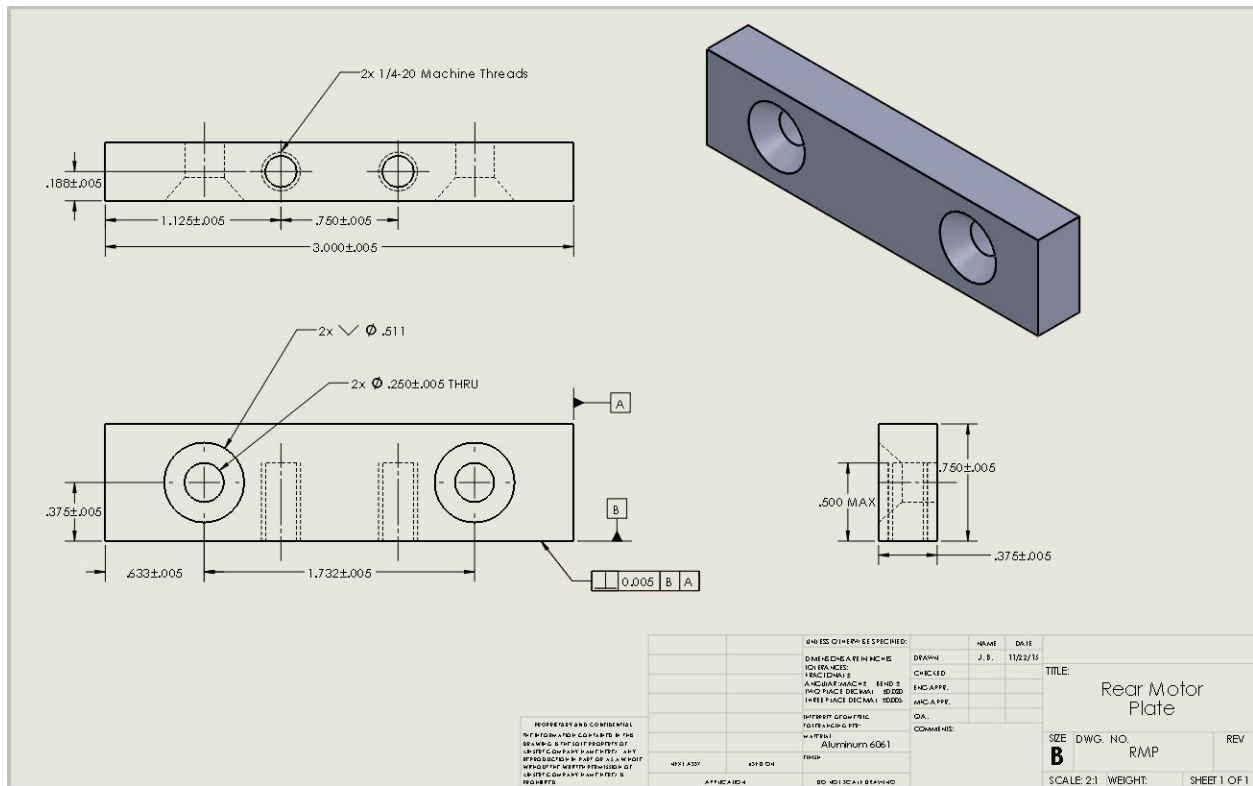


Figure 5: Motor Platform.

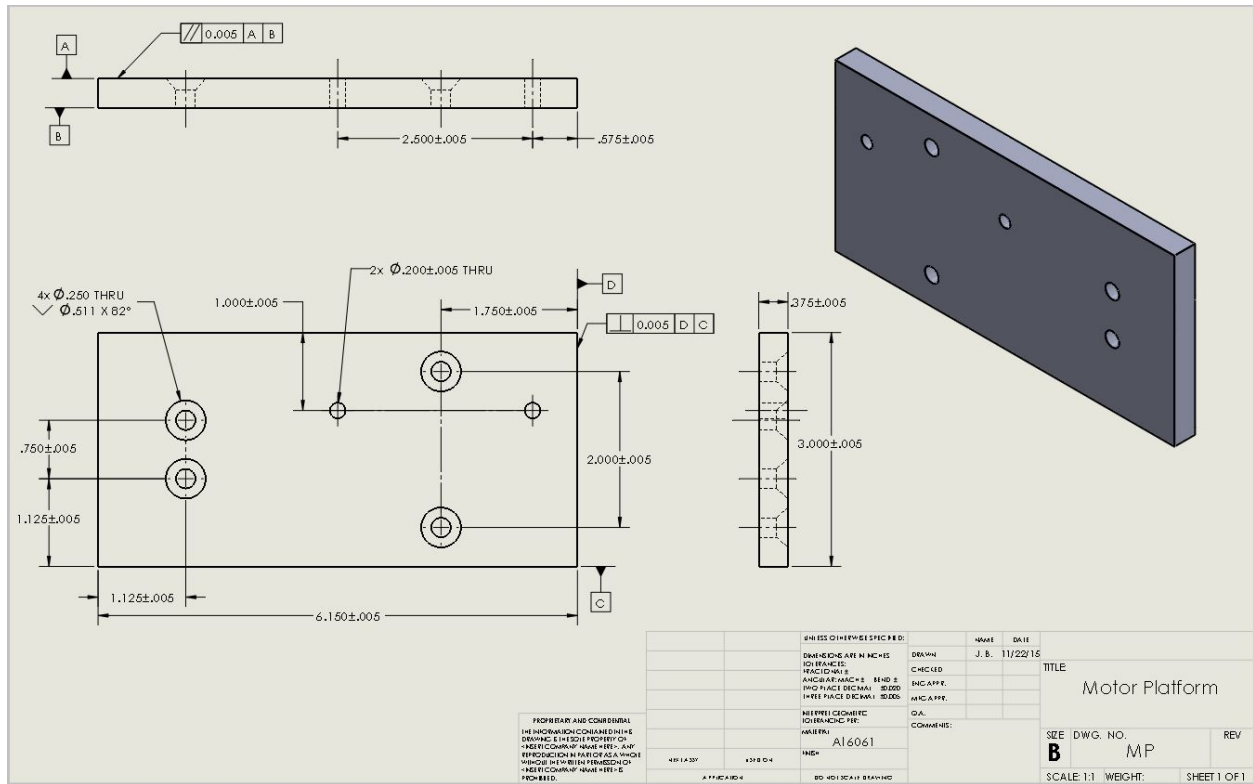


Figure 6: Platform Lever.

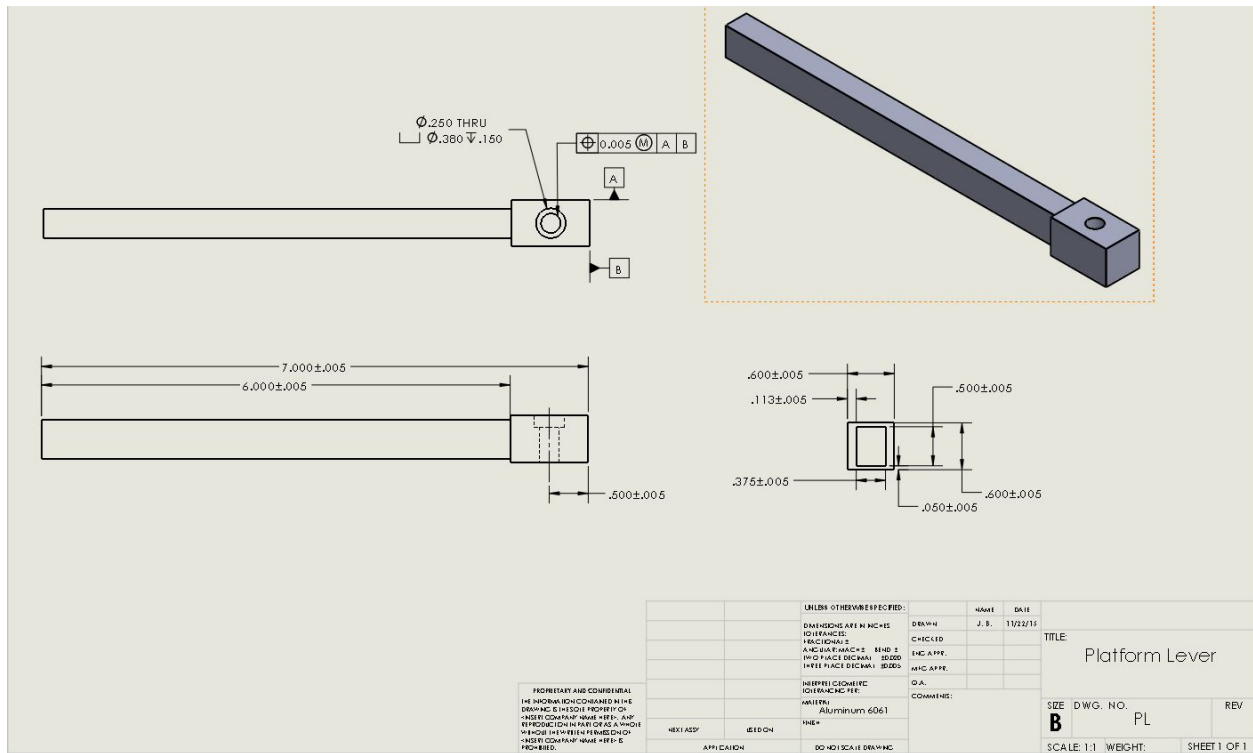


Figure 7: Shaft.

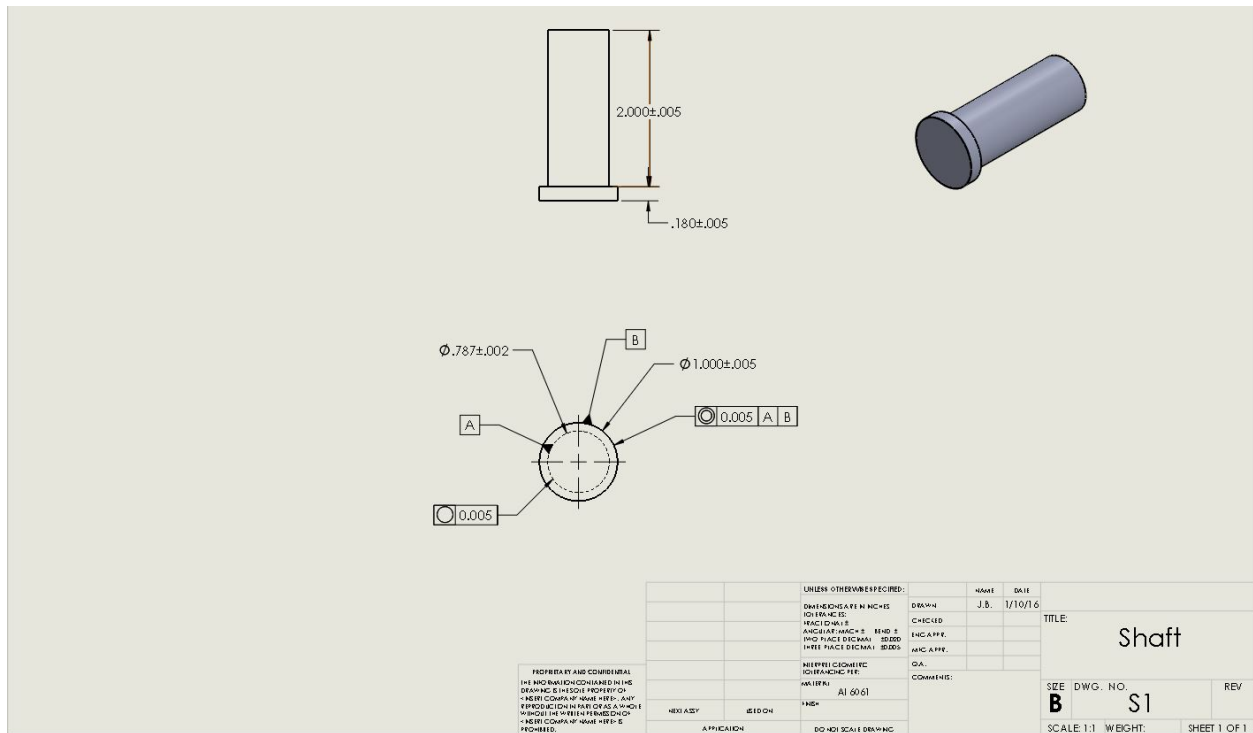


Figure 8: Shaft Housing.

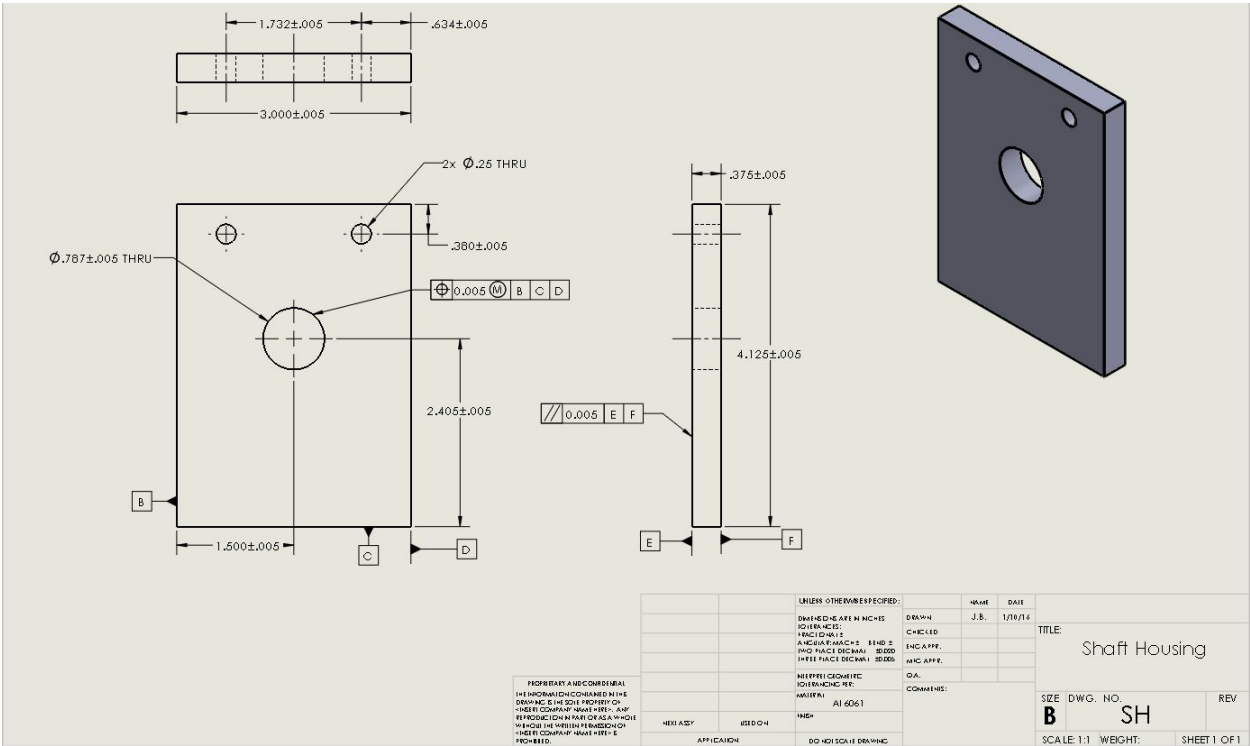


Figure 9: Load Cell Base.

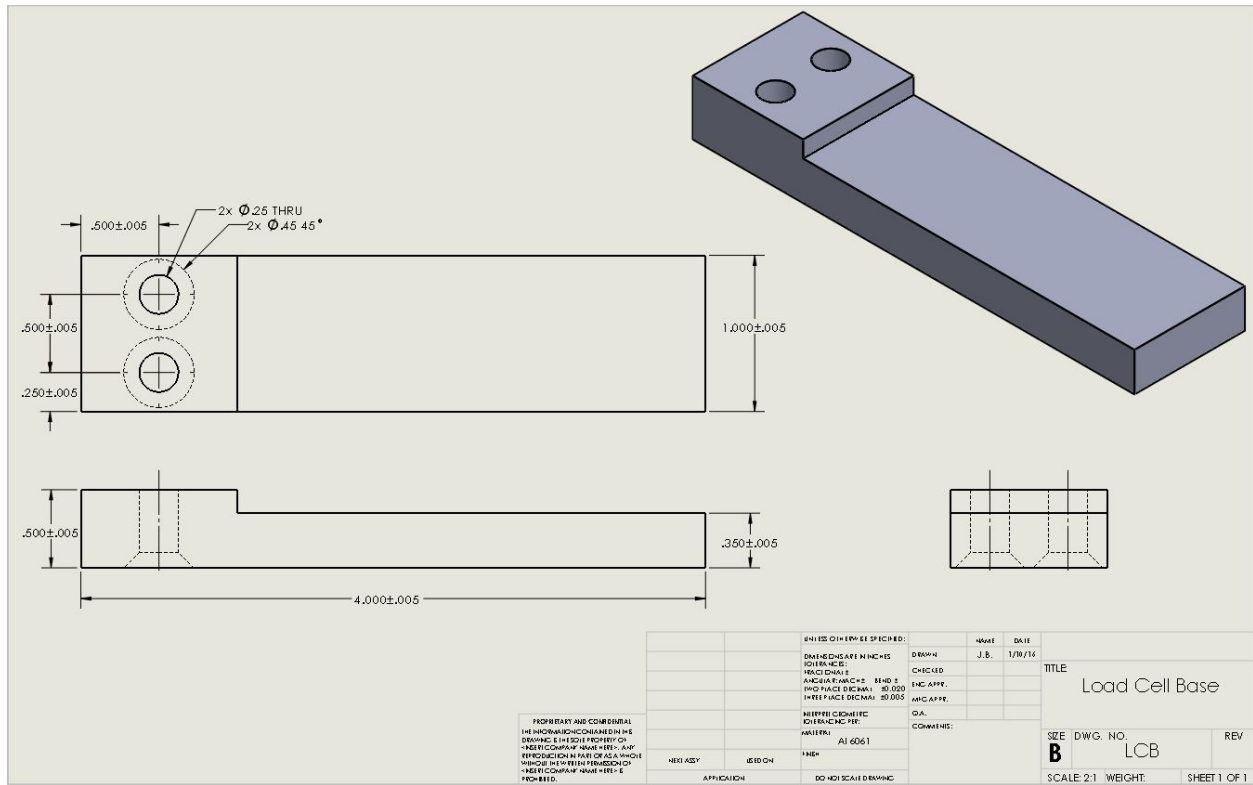
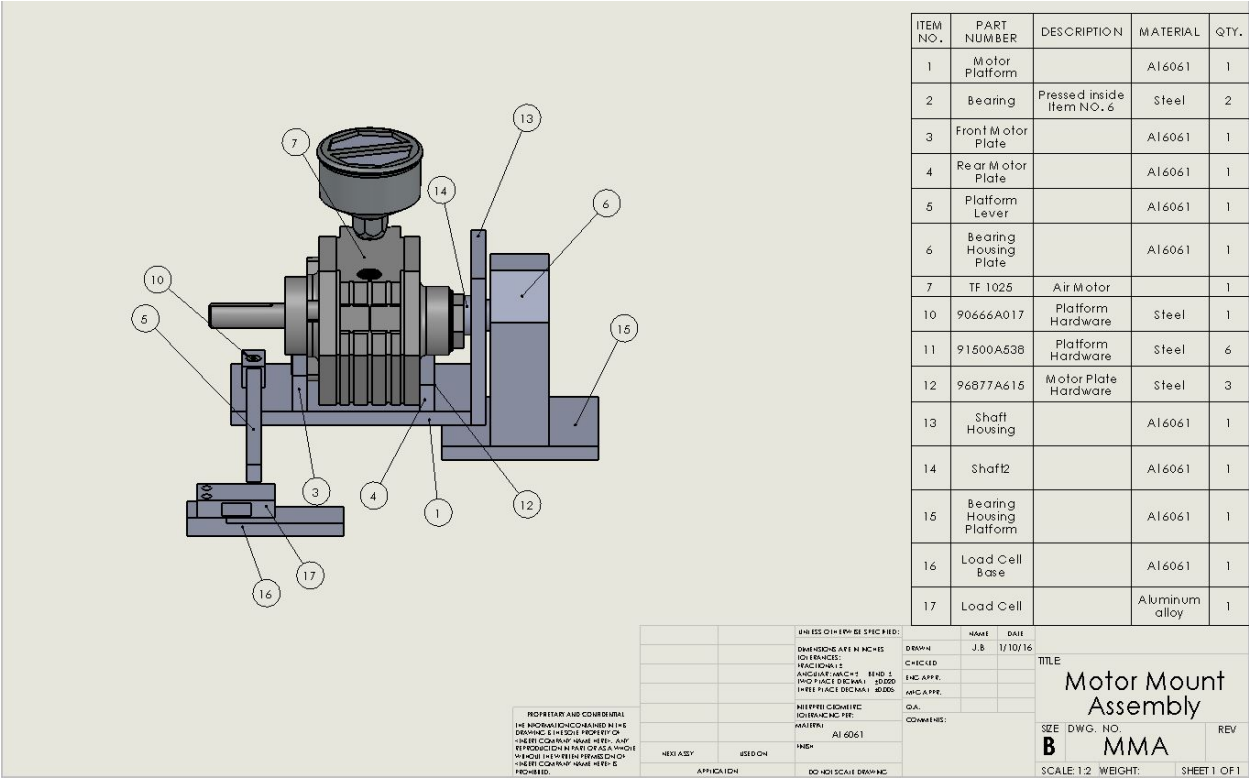


Figure 10: Motor Platform Assembly.



## APPENDIX C – Parts List

<b>Parts</b>	<b>ID/Drawing #</b>
Shaft	S1
Bearings (x2)	BRGS
Front Motor Plate	FMP
Rear Motor Plate	RMP
Shaft Housing	SH
Bearing Housing Platform	BHP
Motor Platform	MP
Platform Lever	PL
Load Cell	LC
Load Cell Display	LCD
Bolts	BLT
Load Cell Base	LCB
Bearing Housing Plate	BHP2



## APPENDIX D – Budget

Material	Application	Part ID	Supplier	Quantity	Price/Unit	Subtotal
1" 6061 Al Round stock	Shaft	S1	CWU	2"x3"	0	0
6061 Al Flat plate	Platform Lever	PL	CWU	4.8"x3"x1.5"	0	0
6061 Al Flat plate	Platform & Bearing Housing	FMP, RMP, PSP, SH, BHP, MP, LCB	Ebay	2x(3/8"x4"x14")	8	16
Hardware	Bolting everything together	BLT	CWU	15(1/4x20 bolts)	0	0
Bearings	Hold motor platform	BRGS	Ebay	2	2.5	5
Load Cell	Measure load	LC	Ebay	1	8	8
Digital Load Cell Display	Display load on cell	LCD	Ebay	1	36.21	36.21
					Total	65.21

## APPENDIX E – Schedule

[illegible]

# APPENDIX H – Testing Report

## Introduction:

A testing method was established in order to prove that the device built will measure the torque of the motor to within reasonable values. A parallel beam load cell is used and it seems that it may give different load values if the load is placed on different sections of the load cell. Also, the weight of the whole device including the load cell, the digital read out, and the hardware must be five pounds or less. Besides from those two requirements, the main requirement that was tested for is the torque value, which was supposed to be  $\pm 2$  lb-in of the manufacturer's specifications. When testing the load cell the values obtained will be from a static load, and the weight will be a reading from a scale. The torque values will be obtained from running the air motor hooked up to the water pump at a set inlet pressure while limiting the RPM by closing the outlet of the water pump.

## Method:

In order to run any tests several things are needed. First, the lab rig and all components must be obtained. This includes water tank, hoses, RPM meter, calibration weights, oil mister, and the lab rig with water pump fitted with inlet and outlet pipes. A source of compressed air is very important as well as a second person to help with reading and calling out values. A scale is needed to weight the device and a jig must be made to test the load cell.

The values from the torque test will be put into excel. These values include RPM, load, and length of torque arm. Using excel the torque can be calculated as well as the horsepower and both of these values can be graphed where RPM is on the X-axis and torque and horsepower are on the Y-axis.

To weigh the device it must first be removed from the rig and place everything on the scale at once including the load cell and readout. In order to test the load cell a jig that fits concentric with the holes on the cell must be machined. Finally, to test the whole device the air motor will be ran in conjunction with the water pump and a water source, which is the source that will place a load on the motor allowing it to produce torque.

Due to safety reasons there are some limitations on the operation of this device. The air motor and the water pump are quite old and therefore it may not be safe to push the motor to 3000 RPM at an inlet pressure of 100 psi. At an inlet pressure of just 60 psi the pressure at the outlet of the water pump rises to over 100 psi when the valve is closed in order to lower the RPM and obtain load cell values at lower RPM.

The precision of the torque values will be affected by the precision to which the length of the torque arm was machined; it will also be affected by the accuracy of the load cell and the precision to which the digital readout calculates the load values. The precision to which the components are machined will not affect the overall performance of the device, except for the concentricity of the bearings with the motor's shaft, but this can be easily adjusted.

The data will be presented in tables and graphs. The test for the load cell will have several load values of different sections of the load cell and they will be organized in a table. The weight of the device is not as important yet it will be placed in a table comparing the requirement and the actual value. The torque values will be calculated in a spreadsheet and presented in a table and a graph.

## Procedure:

Load Cell Calibration: The load cell used is a parallel beam load cell and therefore there is not center spot where the load should be placed. Because of this one is not sure where to place the load in order to obtain the best results. This test can be done anywhere as long as the load cell, digital readout, calibration weight (200g was used), test jig, and battery are present. This test can take up to two hours including the machining time spent making the test jig. For this test access to the machine shop is required.

1. On the lathe turn a disk out of aluminum 0.25 inches thick and 1.25 inches in diameter.
2. Drill a hole to press fit a bolt or a pin equal to the diameter of the holes on the load cell. Cut the head off of the bolt before pressing it in.
3. Obtain a nut and thread it onto the bolt all the way up to the disk. This will concentrate the load over a smaller surface area.
4. Place the test jig into the front hole on the load cell. Zero out the load cell.
5. In the digital readout menu select the mass of the calibration weight to be used.
6. Center the weight on the jig and press both the function and right buttons on the load cell.
7. Record the value on the readout.
8. Repeat steps 4-7 for the rear hole and record the value. The test can be repeated with different calibration weights and it can be repeated several times and the results can be averaged.

Weight of Device: This is a simple test to check for a requirement. This requirement was placed in order to keep the lab rig as light as possible. Overall it will not affect the torque results. The portion that could affect the torque values is all the components that turn with the air motor, that includes both rear bolt plates, upper and lower supports, torque arm, shaft housing, shaft and nut, and all the bolts and pins. Because all these components turn with the bearings which are practically a frictionless surface it is like the motor has no extra mass to turn. This test can be done anywhere where a scale is available and it should take no more than 45 minutes including tear down and reassembly time.

1. Unbolt the device from the rear of the motor and from the lab rig platform.
2. Do not take the device itself apart.
3. Remove the load cell and readout from the lab rig.
4. Obtain a scale with a range of at least 15 lbs.
5. Zero out the scale and place the torque device, load cell, digital readout, and hardware on the scale.
6. Record this value and compare it to the requirement of 5 lbs.

Torque Measurement: For this test not every sensor on the lab rig is needed. The only components needed are the motor, water pump, some hoses, oil mister, water tank, compressed air, RPM meter, and the torque measuring device. This test can take between two to three hours depending on the knowledge of how everything is hooked up.

1. Obtain the components and bolt the torque device to the back of the motor and to the lab platform.
2. Use a calibration weight to calibrate the load cell before placing it under the torque arm.
3. Fix the load cell under the torque arm and tightly press a piece of rubber on the pivot arm on the opposite side of the torque arm.
4. Hookup the oil mister to the inlet of the motor and to the compressed air source. Maintain both valves fully closed.
5. On the oil mister preset the inlet pressure to 20 psi. For better results slowly open the air inlet valve to the motor to full throttle as you set the inlet pressure.
6. Slowly open the air inlet valve to full throttle as you slightly close the water outlet valve to keep the motor from revving up to high revolutions.
7. Use the valve for the water outlet on the water pump to control the RPM.
8. Close the water outlet valve until you reach a desired RPM. This RPM can range from 1000 to 1700.
9. Record load values from the load cell read out at three different RPM for three trials each.
10. Repeat steps 5-9 for 40 psi and 60 psi. Any higher inlet pressure can be potentially dangerous.
11. Insert load, and RPM readings along with the length of torque arm (3.250) into an excel spreadsheet.
12. Calculate the torque by multiplying the load and length of the torque arm. Convert units to lb-in if desired.
13. Graph Torque vs. RPM and Horsepower vs. RPM.

**See Appendix I for test results.**

## Deliverables:

The final results are mass values in pounds, load cell values in grams, and torque values in lb-in. In order for these torque values to be considered successful then they must be within 5% of the manufacturer's specifications. If the values are father off then it must be due to concentricity issues, and the electronic components being of low quality.

A parallel beam load cell seems like a new thing around this department and nobody had good input on them. Using a button load cell is simple since the load just has to be centered on it. On the parallel beam load cell there is enough surface area that the load can be moved around. What is not known is if the load reading will change if the load is placed on different spots on the load cell. Because of this a test was designed. This test would define if the load cell would have to be fixed in place or allowed to move freely while running the lab. In the end it was discovered that no matter where the load was placed the load reading did not change, but only by a few grams. This change in the load reading will not make a big impact on the overall torque calculations since those loads are expected to be a couple thousand grams.

The lab rig itself is quite a heavy object and therefore it was set forth that the torque measuring device must not weigh over five pounds. There was no clear prediction of how much the whole device would weigh since in the end it would not affect the workability of the device.

It was more of a requirement to keep in mind and not something to really try to achieve. In the end the device ended up being around 4.80 lb.

For the torque calculations a test was devised in order to try and match the manufacturer's torque specs. The manufacturer provided a graph of the torque at different inlet pressures and through the maximum limit of RPM. The graphs in Appendix I show the results. These results are not close at all to what the manufacturer specified. This is due to the motor and water pump being a little old, but mostly because the electronic components, that is the load cell and digital readout are not of the highest quality and therefore do not produce accurate results with good repeatability. These two items are far more accurate with a static load, but when vibrations are added the digital readout cannot keep up with the changes in load on the load cell. The best way to fix this problem is to somehow connect the load cell to a data logger program such as LabVIEW and take a moving average to get rid of all the noise.

# APPENDIX I – Testing Data

## Test 1: Load cell calibration data

Trial	Calibration Weight	Hole 1 Load (g)	Hole 2 Load (g)
1	200 g	200.45	200.67
2	200 g	200.36	200.50
3	200 g	200.60	200.51

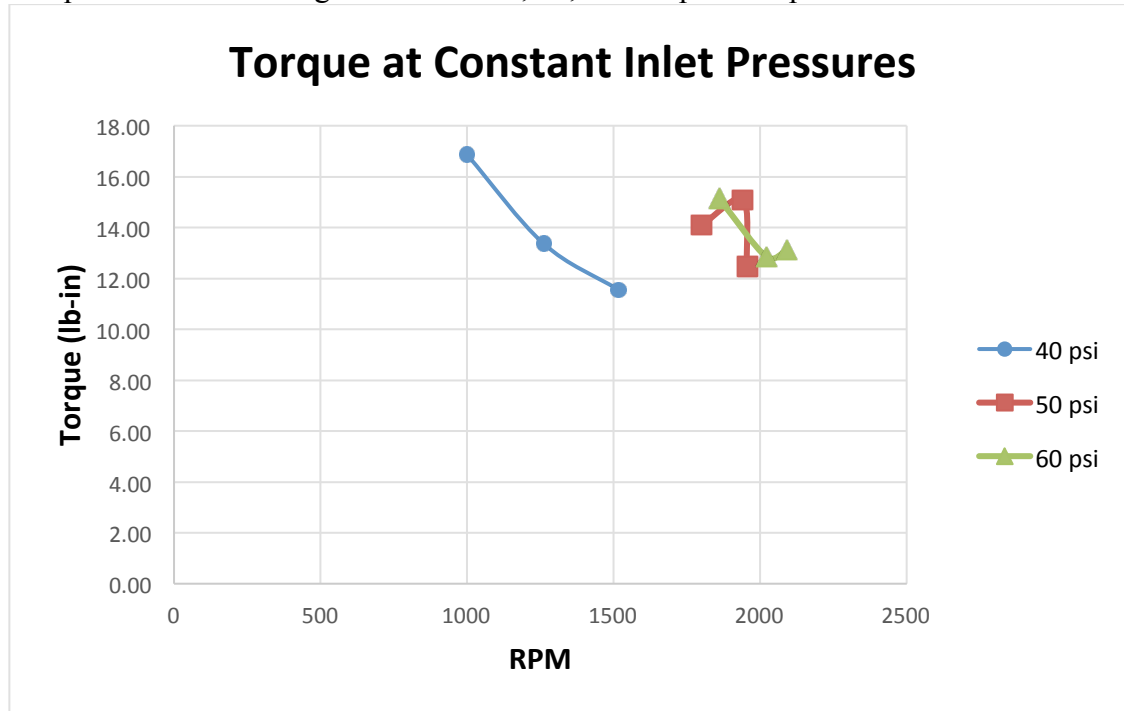
## Test 2: Mass of device and hardware

Trial	Mass (lb)
1	4.76
2	4.80
3	4.85
Average	4.80

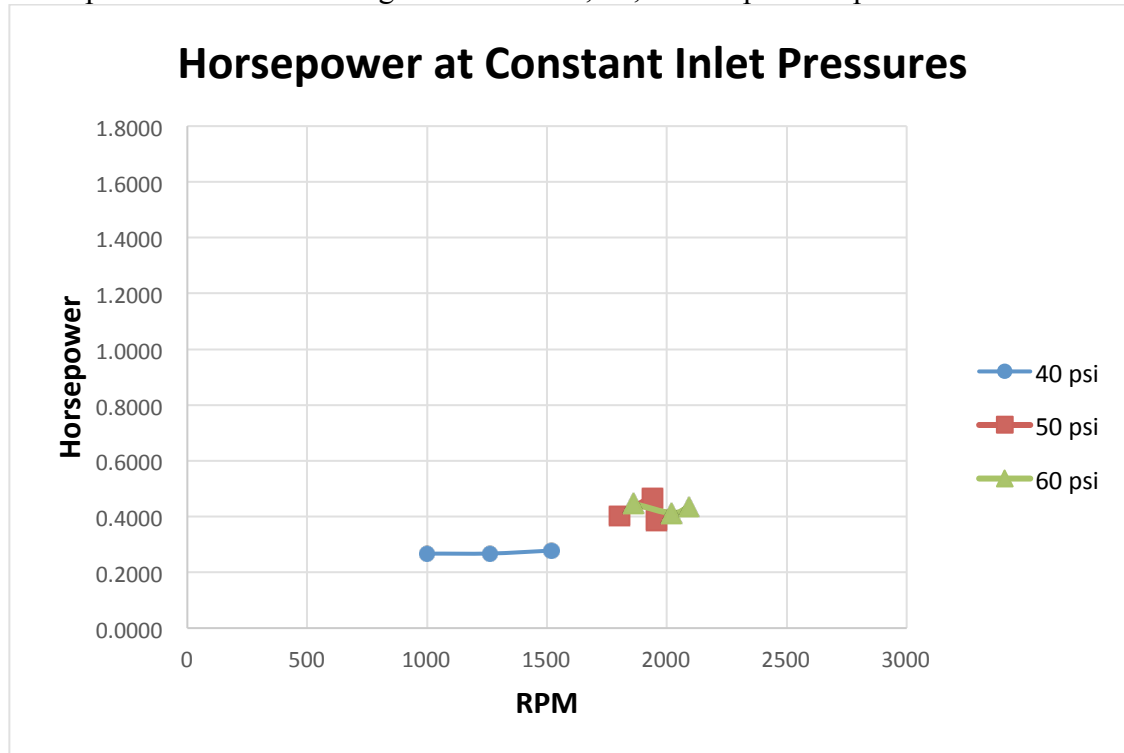
## Test 3: Torque calculations

Inlet Pressure (psi)	RPM	Load (g)	Torque Arm Length (in)	Torque (g-in)	Torque (lb-ft)	Horsepower	Torque (lb-in)
40	1000	1700	4.5	7650	1.406	0.2676	16.87
40	1261	1347	4.5	6062	1.114	0.2674	13.37
40	1518	1163	4.5	5234	0.962	0.2779	11.54
50	1800	1422	4.5	6399	1.176	0.4030	14.11
50	1941	1521	4.5	6845	1.258	0.4648	15.09
50	1955	1256	4.5	5652	1.039	0.3866	12.46
60	1859	1526	4.5	6867	1.262	0.4466	15.14
60	2021	1295	4.5	5828	1.071	0.4121	12.85
60	2092	1322	4.5	5949	1.093	0.4354	13.12
40	1278	1232	4.5	5544	1.019	0.2479	12.22
40	1500	1120	4.5	5040	0.926	0.2645	11.11
40	1767	1281	4.5	5765	1.059	0.3564	12.71
50	1762	1570	4.5	7065	1.298	0.4355	15.58
50	1824	1360	4.5	6120	1.125	0.3906	13.49
50	2025	1330	4.5	5985	1.100	0.4240	13.20
60	1821	1475	4.5	6638	1.220	0.4229	14.64
60	2078	1280	4.5	5760	1.058	0.4188	12.70
60	2180	1160	4.5	5220	0.959	0.3981	11.51

Torque calculated during first trial at 40, 50, and 60 psi inlet pressures.

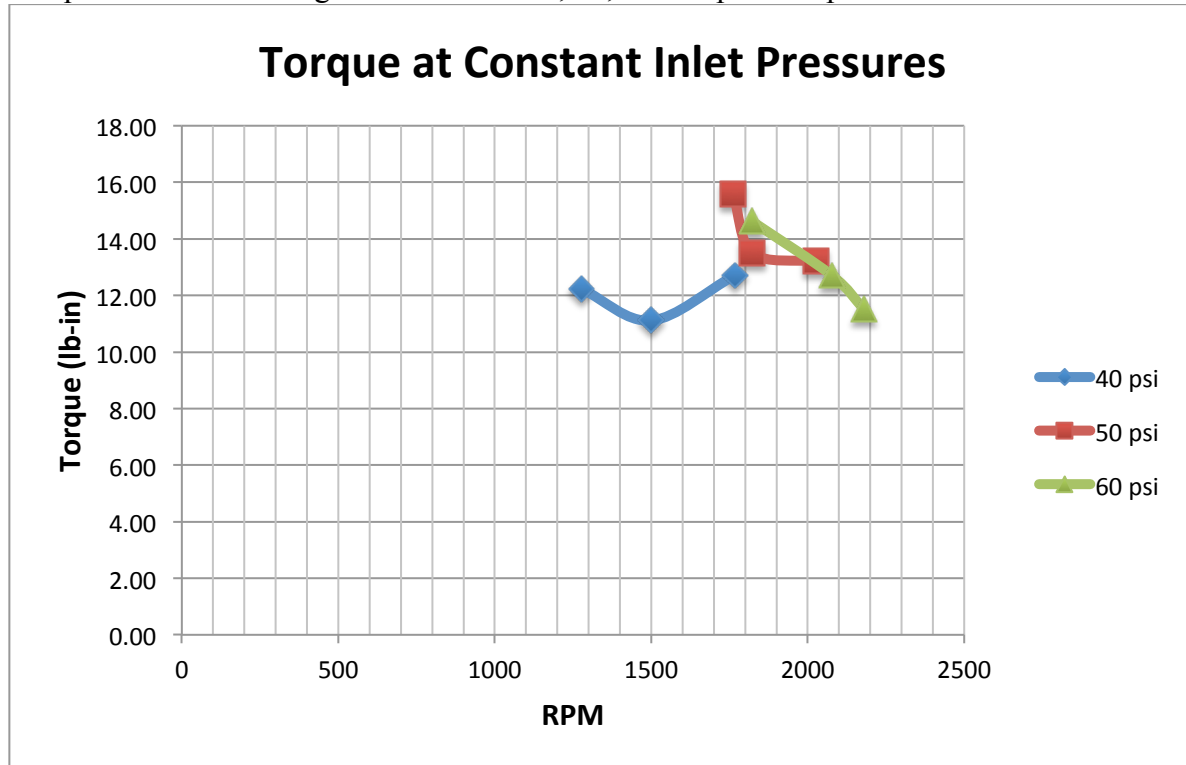


Horsepower calculated during first trial at 40, 50, and 60 psi inlet pressures.

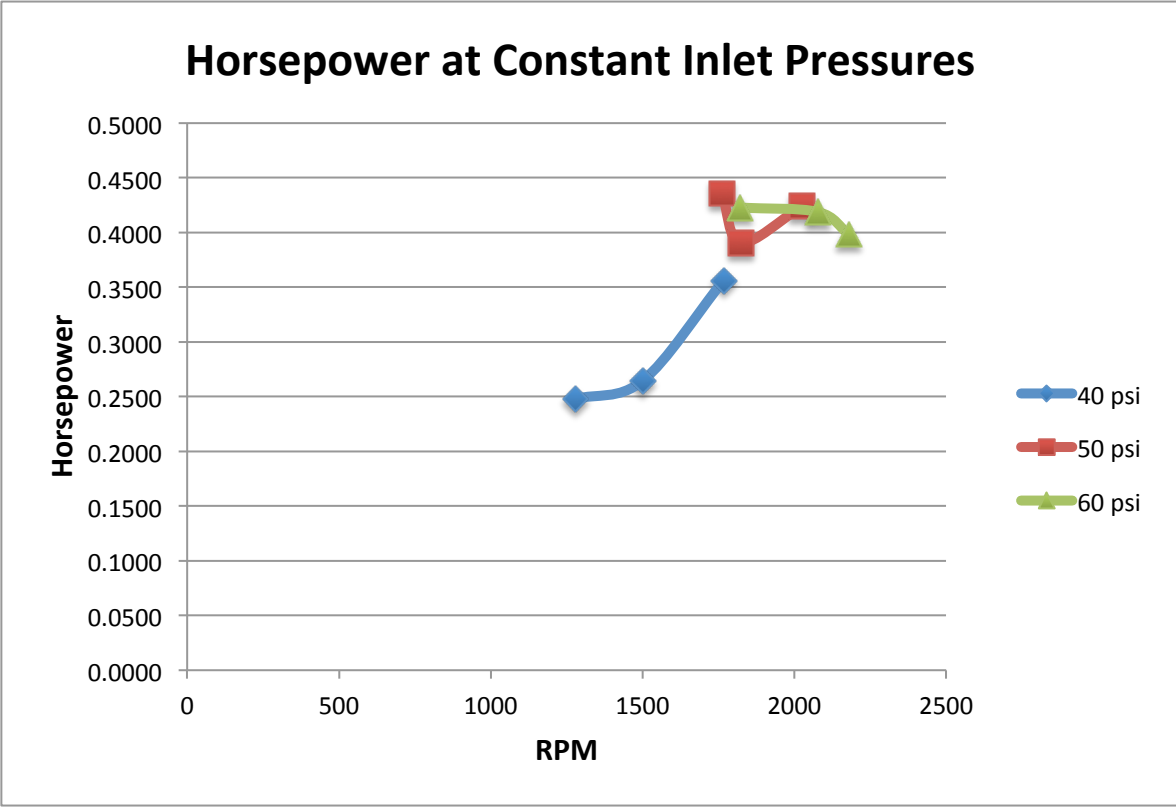




Torque calculated during second trial at 40, 50, and 60 psi inlet pressures.



Horsepower calculated during second trial at 40, 50, and 60 psi inlet pressures.



# APPENDIX J – Resume

## Jose Bejar

2102 N Walnut St Apt 21  
Ellensburg, WA 98926  
Email: jbejar91@hotmail.com  
Cell: (509) 306-9548

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### Objective

I am a Mechanical Engineer Technology student seeking a position as...

### EDUCATION

<b>Bachelor of Science</b> University of Washington, Seattle, WA Mechanical Engineering Degree not completed	2010-2013
<b>Bachelor of Science</b> Central Washington University, Ellensburg, WA Mechanical Engineering Technology	2014-Now

### Relevant Skills

#### Personal Skills

- Ability to work independently and collaboratively.
- High level of organization.
- Ability to follow instructions orally or written.

#### Computer Skills

- SolidWorks
- AutoCAD
- MATLAB
- Visual Basic
- Java

#### Mechanical Aptitude

- Programming for Milltronics CNC Mill
- Programming for Milltronics CNC Lathe
- Bridgeport Mill

- Manual Lathe

### **Employment History**

#### **Central Washington University, Ellensburg WA**

Sept 2015-Now

##### **Lab Technician for the MET Department**

- Handle the material for the basic and advanced machining classes.
- Help students with their MET255 (Basic Machining) projects.
- Maintain the shop clean
- Work on assigned projects by my supervisor.

#### **RAM Mounts, Seattle, WA**

Sept-Dec 2013

##### **Machine Operator**

- As part of a team of around five people we managed up to eight injection-molding machines at times in a fast paced environment.
- We made sure the machines never stopped running by keeping the raw material flowing from the hoppers and making sure the parts were coming out within the quality specifications.

#### **Mold Rite Inc., Woodinville, WA**

July-Sept 2012

##### **Assembly Line Worker**

- Assembled parts that came off of the injection molding machines, checked for quality, counted and packaged them.
- Worked in the tool room milling parts, checking for quality, and packaging them.